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Search for a narrow, spin-2 resonance decaying to a pair of Z bosons in the $q\bar{q}\ell^+\ell^-$ final state

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Abstract

Results are presented from a search for a narrow, spin-2 resonance decaying into a pair of Z bosons, with one Z-boson decaying into leptons (e^+e^- or $\mu^+\mu^-$) and the other into jets. An example of such a resonance is the Kaluza–Klein graviton, G_{KK}, predicted in Randall–Sundrum models. The analysis is based on a 4.9 fb^{-1} sample of proton-proton collisions at a center-of-mass energy of 7 TeV, collected with the CMS detector at the LHC. Kinematic and topological properties, including decay angular distributions as a novel feature of the analysis, are used to discriminate between signal and background. No evidence for a resonance is observed, and upper limits on the production cross sections times branching fractions are set. In two models that predict Z-boson spin correlations in graviton decays, graviton masses are excluded lower than a value which varies between 610 and 945 GeV, depending on the model and the strength of the graviton couplings.

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*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics does not include an explanation of the large difference between the typical scales of gravity and the other fundamental forces (i.e., the "hierarchy problem"). This problem can be overcome by adding one warped spatial dimension to space-time, according to the Randall–Sundrum model [1, 2]; in such a scenario, the existence of Kaluza–Klein excitations of a spin-2 boson, the graviton, is predicted. These models have two fundamental parameters: the mass M_1 of the first graviton mode, referred to as G_{KK} in the following, and the dimensionless coupling strength $\tilde{k} = k/\overline{M}_{Pl}$, where k is the curvature of the warped space and $\overline{M}_{Pl}$ the reduced Planck mass ($\overline{M}_{Pl} \equiv M_{Pl}/\sqrt{8\pi}$).

In the Randall–Sundrum model discussed above (RS1), the graviton decay channels to diphotons and dileptons are the most sensitive, and several searches for such signatures of the RS1 scenario have been performed at the Tevatron [3–5] and at the Large Hadron Collider (LHC) [6–9]. However, different scenarios with warped extra dimensions (ED) allow the SM fields to propagate in the ED [10–12], resulting in a suppression of decays to diphotons and dileptons. These models are more compatible with electroweak precision tests and limits on flavor-changing neutral current processes than the original RS1. Furthermore, they are characterized by different couplings of the graviton to the SM fields. Such couplings result in two distinctive effects: the branching fraction to SM vector-boson pairs can become dominant for certain values of the model parameters, and an enhancement in the longitudinal polarization of the resulting vector boson pairs is predicted.

The CDF and ATLAS experiments have searched for beyond-SM particles decaying to ZZ pairs in the $2\ell 2q$, 4ℓ and $2\ell 2\nu$ final states [13, 14], without specific requirements on the spin or the production mechanism of the particle. This Letter presents a search for heavy narrow spin-2 resonances in the ZZ final state and investigates both the original RS1 model and the Agashe-Davoudiasl-Perez-Soni (ADPS) model [10]. The distinct angular distributions resulting from different polarizations in the decay are exploited to enhance the signal sensitivity. The process studied, $G_{KK} \rightarrow ZZ \rightarrow q\overline{q}\,\ell^+\ell^-$ ($\ell = e, \mu$), combines a high branching fraction with good mass resolution and limited background rates. The dominant background is Z-boson production with associated jets ("Z+jets"). The cross section for this process falls rapidly with the invariant mass of the candidate Z-boson pair, m_{ZZ}.

2 Event reconstruction and selection

We search for a fully reconstructed decay chain of the graviton $G_{KK} \rightarrow ZZ \rightarrow q\overline{q}\,\ell^+\ell^-$, where the charged leptons $\ell^\pm$ are either both muons or both electrons, and each quark is associated with a jet in the Compact Muon Solenoid (CMS) detector. This search covers a graviton mass range between 400 and 1200 GeV. At higher masses, the two jets from the hadronic Z-boson decay merge into one, therefore the efficiency of the present search signature is degraded.

A detailed description of the CMS detector can be found in Ref. [15]. In the cylindrical coordinate system of CMS, ϕ is the azimuthal angle and the pseudorapidity (η) is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the counterclockwise-beam direction. The central feature of the CMS detector is a 3.8 T superconducting solenoid of 6 m internal diameter. Within the field volume are the silicon tracker, the crystal electromagnetic calorimeter (ECAL), and the brass-scintillator hadron calorimeter (HCAL). The muon detectors are located outside the solenoid and are installed between the layers of the steel yoke of the flux return. In addition, CMS has extensive forward calorimetry, in particular two steel/quartz-fiber hadron forward (HF) calorimeters, which cover the pseudorapidity range $2.9 < |\eta| < 5.2$.

Although the main sources of background are estimated from data, Monte Carlo (MC) simulations are used to develop and validate the methods used in the analysis. Background samples are generated using either MADGRAPH 5 [16], SHERPA 1.13 [17], or PYTHIA 6.4.24 [18]. Signal events are generated at Leading Order (LO), for both the RS1 and the ADPS model, using a dedicated generator described in Ref. [19]. Parton distribution functions (PDFs) are modeled using the parameterizations CT10 at next-to-LO [20] and CTEQ6 [21] at LO. For both signal and background MC, events are simulated using a GEANT4-based model [22] of the CMS detector and processed using the same reconstruction algorithms as for data.

Muons are measured with the silicon tracker and the muon system [23]. Electrons are identified as tracks in the tracker pointing to energy clusters in the ECAL [24]. Muons and electrons are required to have the component of momentum transverse to the pp beam direction, p_T, greater than 20 GeV. At least one lepton must have $p_T > 40$ GeV. Leptons are measured in the pseudorapidity range $|\eta| < 2.4$ for muons, and $|\eta| < 2.5$ for electrons. Electrons in the transition range between the barrel and endcap, $1.44 < |\eta| < 1.57$, are excluded. Both the p_T and η requirements are consistent with those in the online trigger selection requiring two charged leptons, either electrons or muons.

Muons are required to be isolated from hadronic activity in the detector by restricting the sum of transverse momentum (energy) in the tracker (ECAL and HCAL), within a surrounding cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ (excluding the muon candidate itself), to be less than 15% of the measured p_T of the muon, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and in azimuthal angle. Electron isolation requirements are similar, but vary depending on the shape of the electron shower. The details of electron and muon identification criteria are described in Ref. [25].

Jets are reconstructed with the particle flow (PF) [26] algorithm. Reconstructed particle candidates are clustered to form jets with the anti-k_T algorithm [27] with a distance parameter of 0.5. Jets are required to be inside the tracker acceptance ($|\eta| < 2.4$) and to have $p_T > 30$ GeV. Jets that overlap with isolated leptons within $\Delta R = 0.5$ are removed. Jet energy corrections are applied to account for the non-linearity due to instrumental effects. These corrections are based on in-situ measurements using dijet, γ+jet and Z+jets data samples [28]. A quality selection, primarily based on the energy balance between charged and neutral hadrons, is applied to remove spurious jets due to detector artifacts. The jet four-momentum is corrected for the contribution of overlapping minimum bias events coming from different proton-proton collisions (pileup) based on the effective jet area, following Ref. [29].

Each pair of oppositely charged leptons and each pair of jets passing the above selections are considered as Z candidates. Background suppression is primarily based on the dilepton and dijet invariant masses, $m_{\ell\ell}$ and m_{jj}. The requirement $75 < m_{jj} < 105$ GeV is applied in order to reduce the Z+jets background, and $70 < m_{\ell\ell} < 110$ GeV to reduce background without a genuine Z decaying to leptons, such as $t\bar{t}$.

The kinematics of the jets is corrected by constraining the invariant mass of the dijet system to the mass of the Z boson. Experimental resolutions, typically lower than 10%, are taken into account in the kinematic fit. The statistical analysis is based on the invariant mass of the graviton candidate, m_{ZZ}, calculated by imposing the kinematic constraint to the dijet system.

2.1 Jet flavor analysis

As the dominant background is Z+jets ($Z \to \ell^+\ell^-$) production, we use the flavor content of the jets compared to those from Z-boson decays to discriminate against it. In Z+jets events the

jets will predominantly be produced by the fragmentation of low-mass quarks and gluons. As a result, we can exploit the fact that, in ZZ events with one Z-boson decaying into jets, there will be a larger fraction of jets from heavy-quark fragmentation than from Z+jets, and there will be no jets from gluon hadronization. We take advantage of both features by tagging the b flavor and introducing a likelihood discriminant that separates gluon and light-quark jets on a statistical basis, as described in Ref. [30].

To identify jets originating from the hadronization of bottom quarks, we use the CMS track counting high-efficiency (TCHE) b-tagging algorithm [31, 32]. The data are split into three b-tag categories. The 2 b-tag category is required to have one jet with a value of the TCHE discriminant passing the medium working point selection ($\sim$65% efficiency) and the other jet passing the loose working point selection ($\sim$80% efficiency). Events not selected in the 2 b-tag region are categorized as 1 b-tag if they have at least one jet satisfying the loose b-tagging requirement. The 0 b-tag category contains all the remaining events.

For the 0 b-tag category, which is dominated by the Z+jets backgrounds, a quark-gluon discriminant (QG) is constructed from observables related to the multiplicity and distribution of the jet constituents [30]. The QG-discriminant values range from 0 (gluon-like) to 1 (quark-like). We apply a loose requirement, $QG > 0.1$, in the 0 b-tag category only.

In order to suppress the substantial $\mathrm{t\bar{t}}$ background in the 2 b-tag category, a discriminant, λ, is constructed using resolution functions of the PF jets as described in Ref. [33], to provide a measure of the missing transverse energy ($\not\!\!E_{\mathrm{T}}$) significance. We apply a loose requirement, $2\ln\lambda(\not\!\!E_{\mathrm{T}}) < 10$, in the 2 b-tag category only.

2.2 Angular analysis

Due to the tensor nature of the graviton, the angular distribution of its decay products shows a distinct signature. Five angles $(\theta^*, \theta_1, \theta_2, \Phi_1, \Phi)$ defined in Ref. [19] fully describe the kinematics of the $\mathrm{q\bar{q}}, \mathrm{gg} \to \mathrm{G_{KK}} \to \mathrm{ZZ} \to \mathrm{q\bar{q}}\,\ell^+\ell^-$ process. Further kinematic selection exploits these five angular observables, which are only weakly correlated with the invariant masses of $\mathrm{G_{KK}}$ and the two Z bosons, and with the longitudinal and transverse momenta of the graviton candidate.

We construct an angular likelihood discriminant (LD) based on the probability ratio of the signal and background hypotheses, as described in Ref. [30]. These probabilities are parameterized as functions of m_{ZZ}: the full five-dimensional theoretical distributions multiplied by acceptance functions are used for the two signal types, while empirical functions describe the background probabilities. The left panel of Figure 1 shows the distribution of $\cos\theta^*$ after the pre-selection requirements, where θ^* is the polar angle of one of the Z boson momentum vectors in the ZZ rest frame, measured with respect to the beam axis. Because the distributions of the signal and background events are so different, $\cos\theta^*$ is an important part of LD. The right panel of Figure 1 presents the LD distribution after the same pre-selection requirements.The expectation of longitudinal polarization in the ADPS model results in a visible enhancement of the discriminating power of the LD with respect to the Z+jets background.

The figure of merit proposed in Ref. [34] is used to optimize the selection on the angular likelihood discriminant in order to maximize the expected sensitivity to the production of an RS1 graviton. Because of the different background contributions, the optimization is performed independently for the three b-tag categories of events. The results are approximately independent of the graviton mass hypothesis and lead to cut values of $LD > 0.28$, 0.35, and 0.21 for the 0 b-tag, 1 b-tag and 2 b-tag categories, respectively. The optimization is performed only on RS1

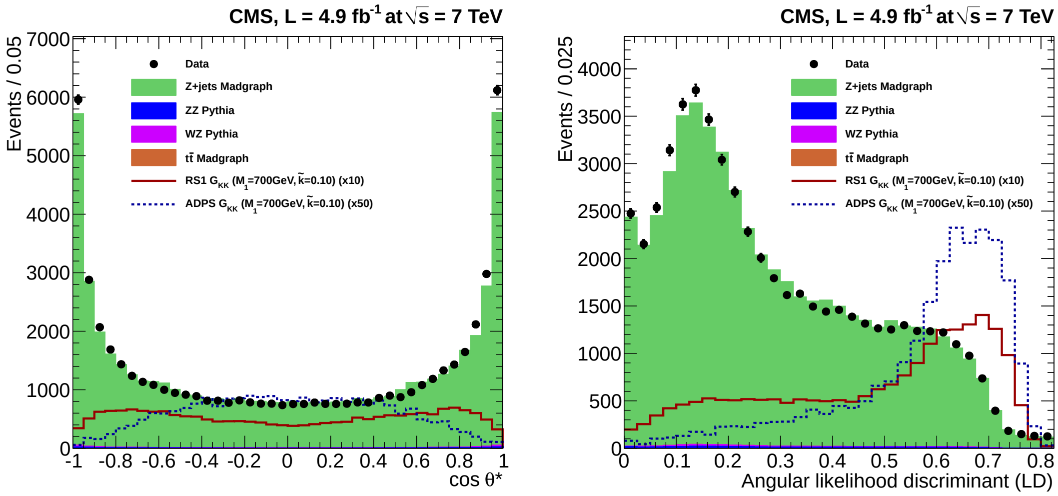

Figure 1: Distributions of the $\cos\theta^*$ variable (left) and the angular likelihood discriminant, LD (right), after pre-selection requirements. Points with error bars show the data distributions. Stacked, filled histograms show the background expectations from simulated events with the different component breakdown. The contribution from Z+jets dominates the background. Solid- or dashed-line histograms (overlaid) show the expected distributions for RS1 and ADPS gravitons with mass $M_1 = 700\,\text{GeV}$ and $\tilde{k} = 0.10$, scaled up by arbitrary factors for illustration.

signal and the same selection criteria are used for both models under scrutiny.

Table 1: Summary of optimized kinematic and topological selection requirements.

	Preselection		
$p_T(\ell^\pm)$	$p_T > 40\ (20)$ GeV		
p_T(jets)	> 30 GeV		
$\lvert\eta\rvert(\ell^\pm)$	$e^\pm$: $\lvert\eta\rvert < 2.5$, $\mu^\pm$: $\lvert\eta\rvert < 2.4$		
$\lvert\eta\rvert$(jets)	< 2.4		
	0 b-tag	1 b-tag	2 b-tags
b-tag	None	One loose	Medium & loose
Ang. LD	> 0.28	> 0.35	> 0.21
QG discr.	> 0.10	none	none
$2\ln\lambda(\not{E}_T)$	none	none	< 10
m_{jj}	[75, 105] GeV		
$m_{\ell\ell}$	[70, 110] GeV		
m_{ZZ}	[375, 1500] GeV		

2.3 Summary of selection

The selection requirements are summarized in Table 1. When an event contains multiple G_{KK} candidates passing these selection requirements, the one with the largest number of b-tagged jets is retained, thus giving preference to the purest category. Further ambiguity between multiple candidates is resolved by selecting the candidate with m_{jj} (before the kinematic fit) and $m_{\ell\ell}$ values closest to the Z boson mass m_Z. Signal selection efficiencies depend on the graviton mass considered and range approximately from 3 to 10% (3 to 21%) for the RS1 (ADPS) model, respectively.

3 Event analysis

3.1 Background estimation

In order to minimize systematic uncertainties associated with the background shapes, we estimate the background distribution from the data. The m_{ZZ} distribution of the selected events is split into three samples based on the number of b-tagged jets. The selected events are then examined comparing to 33 equally-spaced hypothetical graviton masses in the range between 400 GeV and 1200 GeV.

A signal window in the m_{ZZ} distribution is defined around the expected position of the signal peak. The signal shape is parameterized using the sum of a double Crystal-Ball function (i.e., a Gaussian distribution with power-law tails on both sides) [35] and an empirical line-shape derived from the observed distribution of events with misassigned jets (a triangular shape convoluted with a Crystal-Ball function). The latter component describes both mismeasurements and incorrect reconstruction of the graviton decay products. The size of the signal window corresponds to three times the standard deviation of the core distribution of the signal shape, which ranges from 13 (at $M_1 = 400\,\mathrm{GeV}$) to 38 GeV (at $M_1 = 1200\,\mathrm{GeV}$). For every mass value considered, the m_{ZZ} distribution is fitted in the $[375, 1500]$ GeV range after excluding the signal window, in order to estimate the background expectation from the sideband regions. The distributions of m_{ZZ} for the background are parameterized with exponential functions. To gain stability in the fits, we combine the electron and muon samples, assuming that the background shapes are the same.

Figure 2 shows the result of the fit for the specific case of $m_{ZZ} = 700\,\mathrm{GeV}$, overlaid with the m_{ZZ} distributions split by both b-tag category and leptonic channel. While the normalization of the fit is determined independently for each plot, the good agreement between data and fit justifies the use of the same fit function in the eejj and the $\mu\mu jj$ channels. The MC prediction normalized to the integrated luminosity of the data sample is also included in the plot. Although the agreement of the MC prediction with the data is fair, differences are observed in both normalization and shape. The most significant discrepancy between data and MC, in the 0 b-tag category (11% in the total yield), is because the relative fraction of quark- and gluon-originated jets is not well reproduced in MADGRAPH MC, which affects the QG selection efficiency. Because the background is determined directly from the sidebands in the data, the results are not sensitive to the limitations of the simulated samples.

The yields predicted by the background estimation from control samples in data are compared to the observed ones in Table 2. Additionally, the expected number of events for the hypothetical graviton signals in the RS1 and ADPS models are listed for some benchmark mass values.

3.2 Systematic uncertainties

The uncertainties on the normalization of the background fit are statistical in nature since they depend on how many events populate the sidebands. The shape uncertainty is determined by propagating the uncertainty on the slope parameter of the exponential into the background estimation. Because of the steep fall of the m_{ZZ} spectrum, these uncertainties are larger for low values of the graviton masses. In the case of the search for a 400 GeV (700 GeV) resonance, the uncertainties on the normalization and shape of the background are 10% (4%) for the 0 b-tag, 10% (5%) for the 1 b-tag, and 30% (15%) for the 2 b-tag category.

The systematic uncertainties on the signal normalization are summarized in Table 3. We consider effects from lepton energy scale, resolution, selection, and trigger; jet efficiency, energy scale and resolution after calibration; pileup; $E\!\!\!/_{\mathrm{T}}$ significance requirements; heavy-quark flavor

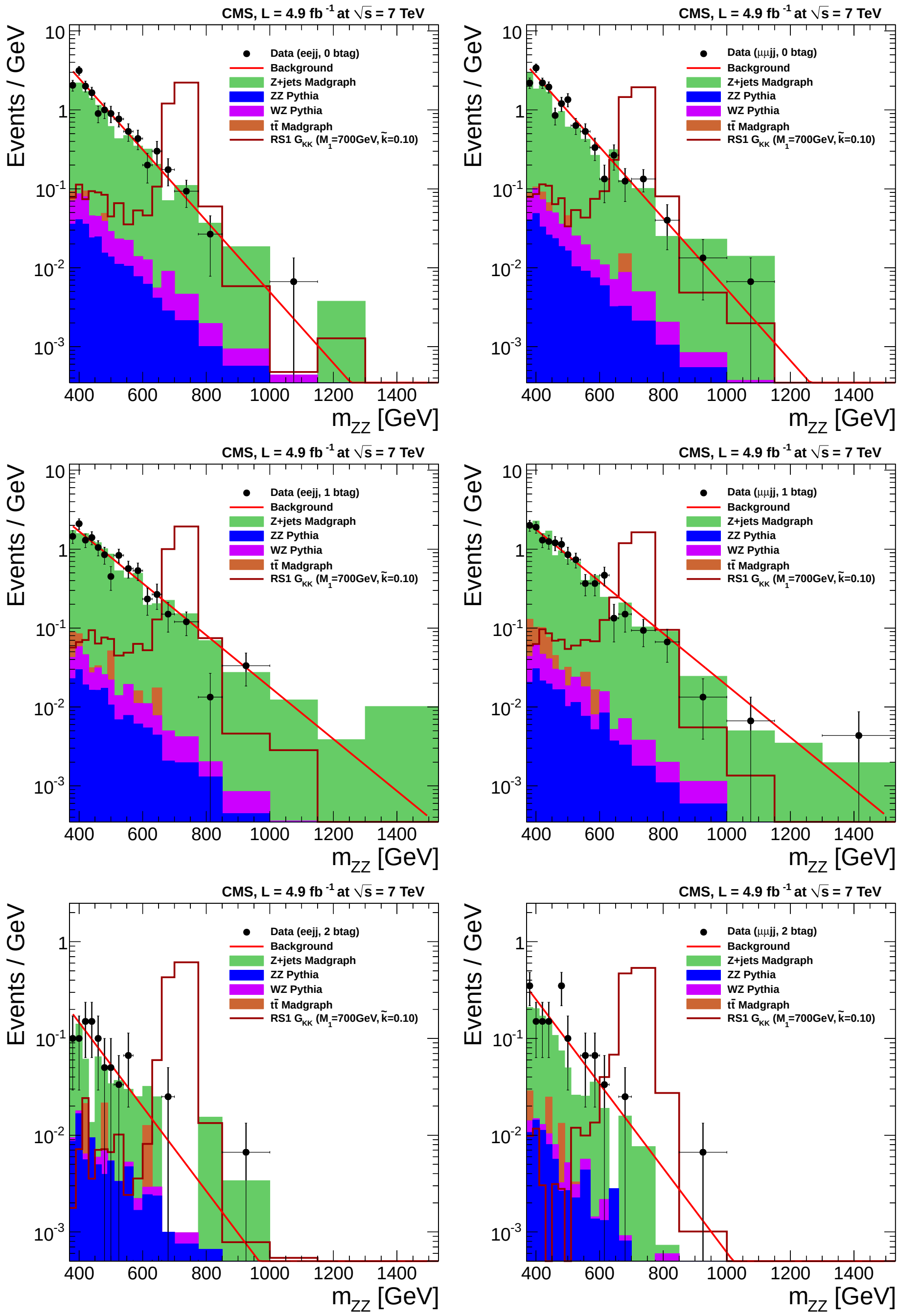

Figure 2: The m_{ZZ} invariant mass distribution after final selection in three categories: 0 b-tag (top), 1 b-tag (middle), 2 b-tag (bottom). The two channels eejj and $\mu\mu jj$ are presented separately on the left and on the right, respectively. Points with error bars show distributions of data, stacked filled histograms show the background expectation from simulated events with the different components illustrated. Also shown is a hypothetical RS1 graviton signal with mass of 700 GeV and $\tilde{k} = 0.10$. The red (lighter) solid line shows the central value of the prediction of background from the sideband extrapolation procedure (excluding a signal window of $\pm$57 GeV around 700 GeV in this example).

Table 2: Observed and expected yields in the 4.9 fb^{-1} dataset at $\sqrt{s} = 7\,\mathrm{TeV}$. The yields are quoted in the range $375 < m_{ZZ} < 1500\,\mathrm{GeV}$ (excluding a signal window of $\pm 57\,\mathrm{GeV}$ around 700 GeV in this example). The signal expectations for the RS1 and ADPS models are reported for three benchmark M_1 points. The uncertainties shown are the sum in quadrature of the systematic and statistical uncertainties.

	0 b-tag	1 b-tag	2 b-tags
Obs. yield	658	542	51
Exp. bkgnd	652±25	548±23	51±7
Signal expectation (RS1 graviton, $\tilde{k}$=0.10)			
500 GeV	268±24	212±16	100±12
700 GeV	50±5	39±4	12.4±1.6
900 GeV	8.4±1.2	7.2±0.8	1.36±0.24
Signal expectation (ADPS graviton, $\tilde{k}$=0.10)			
500 GeV	120±10	102±6	42±5
700 GeV	11.3±1.2	10.9±0.7	3.2±0.4
900 GeV	0.78±0.10	0.71±0.05	0.097±0.012

tagging and quark-gluon discrimination; graviton production mechanism; and the luminosity measurement.

Reconstruction efficiencies for leptons and their uncertainties are evaluated from control samples in data [25]. The systematic uncertainties on jet reconstruction are evaluated by variation of the jet energy scale and resolution within calibration uncertainties. Uncertainties due to pileup are taken as the difference between reconstruction and selection efficiencies with the number of pileup vertices shifted by one unit up and down with respect to the average value measured in data. The requirement on the discriminant $\lambda(\not{E}_{\mathrm{T}})$ translates into 1–2% reduction in signal and the resulting uncertainty is taken as the full inefficiency value. Uncertainties on the quark-gluon selection efficiency are evaluated using a selected γ+jet sample in data, which predominantly contains quark jets. The uncertainty on the b tagging has several sources, such as pileup effects and dependence on the fraction of b production from gluon splitting, and has been evaluated on a sample of dijet events enriched in heavy-flavor by requiring a muon to be associated with one jet [32].

For a given production model, there is an additional uncertainty in the production mechanism coming from the choice of PDFs. PDFs affect the distribution of the longitudinal momentum of the graviton, hence the signal acceptance. We follow the PDF4LHC [20, 36–39] recommendation to estimate the uncertainty due to PDF knowledge and to calculate the uncertainty on signal acceptance. The relative uncertainty on the integrated luminosity [40] is also applied to the signal normalization.

4 Results

Based on the normalization and shape of the m_{ZZ} distribution for signal and background, obtained as described in Section 3.1, we perform an unbinned statistical analysis of the results using the same formalism as in [30, 41]. Since no significant excess is observed, we set exclusion limits at the 95% confidence level (CL) on the product of the graviton cross section and the branching fraction of $\mathrm{G_{KK}} \to \mathrm{ZZ}$. The upper limits are calculated using the $\mathrm{CL_s}$ [42, 43] method

Table 3: Summary of sources of systematic uncertainties on signal normalization. All are expressed as relative uncertainties on the cross section.

Source	0 b-tag	1 b-tag	2 b-tags
μ reconst. & trig.		2.7%	
e reconst. & trig.		4.5%	
Jet reconst.		2–4%	
Pileup		1–4%	
$\not\!\!E_{\mathrm{T}}$ significance	–	–	1–2%
b tagging	2–7%	3–5%	10–11%
QG-discrimination	4.6%	–	–
Acceptance (PDF)		$\sim$1%	
Luminosity		2.2%	

and compared to the theoretical cross sections times branching fraction of $G_{KK} \to ZZ$.

Figure 3 (left) shows the upper limits for the RS1 model and compares them to LO theoretical expectations for two benchmark values of the coupling strength $\tilde{k}$, equal to 0.05 and 0.10. These results allow us to exclude at the 95% CL gravitons with $M_1 < 945\,\mathrm{GeV}$ for $\tilde{k} = 0.10$, improving on previous analyses [14] where a phase-space decay model of the graviton is used. For a value of the coupling strength $\tilde{k} = 0.05$, we exclude the separate ranges $M_1 < 720\,\mathrm{GeV}$ and $760 < M_1 < 850\,\mathrm{GeV}$, because of an under-fluctuation of the observed limit around $M_1 = 800\,\mathrm{GeV}$. The upper limit for a signal generated according to the ADPS model is shown in Fig. 3 (right). The limit on the production cross sections times branching fraction of $G_{KK} \to ZZ$, as a function of the graviton mass, is compared to the model predictions at LO, resulting in exclusion ranges of $M_1 < 720\,\mathrm{GeV}$ and $M_1 < 610\,\mathrm{GeV}$ for $\tilde{k} = 0.10$ and 0.05, respectively.

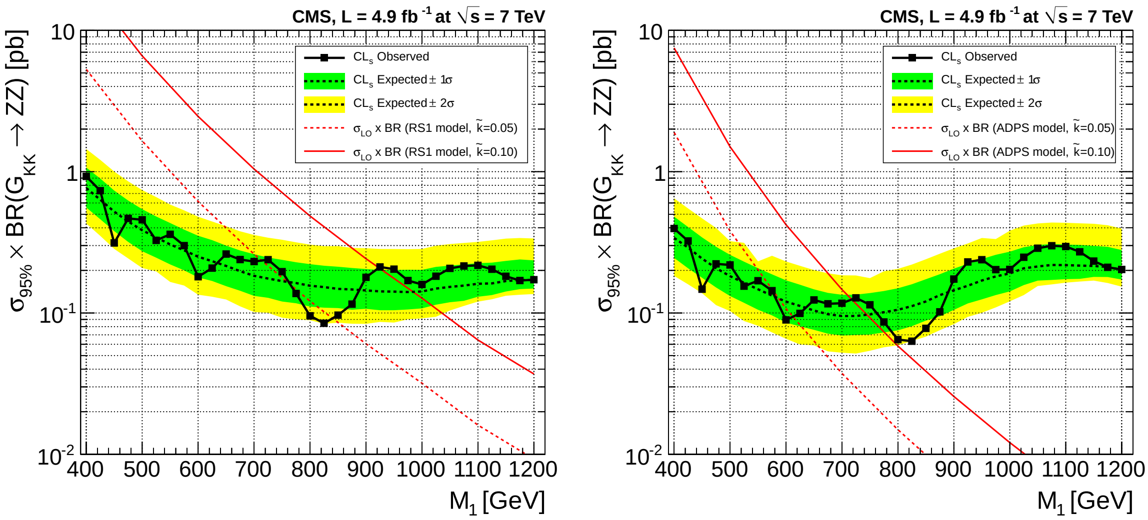

Figure 3: Observed (black solid lines) and expected (black dashed line) 95% CL upper limits on the cross section times branching fraction for $G_{KK} \to ZZ$, obtained with the CL_s technique. The graviton signal was generated according to the model in [1] (RS1, left) and [10] (ADPS, right). The 68% and 95% ranges of expectation for the background-only model are also shown with green (darker) and yellow (lighter) bands surrounding the expected upper limit line, respectively. The predicted product of the graviton cross section and the branching fraction is shown as a red solid (dashed) curve for $\tilde{k} = 0.10$ ($\tilde{k} = 0.05$).

5 Summary

Results have been presented of a search for a KK graviton decaying into ZZ, with one Z-boson decaying leptonically, the other hadronically. CMS data at $\sqrt{s} = 7\,\mathrm{TeV}$ have been used, corresponding to a total integrated luminosity of $4.9\,\mathrm{fb}^{-1}$. As a novel feature of this study, the analysis targets specific graviton models, by exploiting information on angular distributions of the decay products to build likelihood-ratio discriminants that enhance the signal sensitivity.

No excesses in the m_{ZZ} distributions over the expected SM backgrounds are found, for the range 400–1200 GeV. Upper limits on the production cross section times branching fraction as a function of graviton mass are set at 95% confidence level. Exclusion ranges for the RS1 model are $M_1 < 945\,\mathrm{GeV}$ for $\tilde{k} = 0.10$, and $M_1 < 720\,\mathrm{GeV}$ and $760 < M_1 < 850\,\mathrm{GeV}$ for $\tilde{k} = 0.05$.

For the first time, upper limits are obtained specifically for the ADPS model, which is more compatible with current indirect experimental limits than the original RS model. We place exclusion ranges of $M_1 < 720\,\mathrm{GeV}$ and $M_1 < 610\,\mathrm{GeV}$ for $\tilde{k} = 0.10$ and 0.05, respectively.

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